MICRO - STRUCTURE OF CERTAIN HIGH - SPEED STEELS

BY

H. B. PULSIFER

ARMOUR INSTITUTE OF TECHNOLOGY

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Micro-structure of certain
high-speed steels

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MICRO-STRUCTURE

OF

CERTAIN HIGH-SPEED STEELS

A THESIS

PRESENTED BY

H. B. PULSIFER

TO THE

PRESIDENT AND FACULTY

OF

ARMOUR INSTITUTE OF TECHNOLOGY

FOR THE DEGREE OF

CHEMICAL ENGINEER

MAY TWENTY-SEVENTH, NINETEEN HUNDRED FIFTEEN

CHICAGO, ILLINOIS

L. C. Morin,
Draw of Cutt. Studio.

F. M. Raymond

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Acknowledgment.

Professor Harry McCormack, Head of the Department of Chemical Engineering and Director of the Chemical Engineering Laboratories at the Armour Institute of Technology, had the specimens, on which this work was carried out, preserved from former investigations and placed at the author's disposal; he suggested that the work be undertaken, substantially as carried through.

To the Goodwill and Kindly Interest of Professor McCormack is due the completion and presentation of so extensive and expensive an investigation as is here made evident; it is only a matter of regret that this co-operation and the facilities of the Institute have not been able to produce results of even greater value.

Introduction.

The high-speed steels trace their ancestry back to the days of the discovery of tungsten by Scheele and his students and through the dim history of crucible and forge steel; they appear sharply on the stage of human interest after Robert F. Mushet had discovered self-hardening steel by accident in 1868 and the experiments of Fred W. Taylor, which began in 1894 on these self-hardening steels, blossomed out in the great demonstration at the Paris Exposition of 1900.

The work of Taylor led to the manufacture and use of steel for tools which has revolutionized machine practice and made a remarkable advance in the art of cutting metals. High-speed steels have the property of enormous execution at temperatures far above the range of ordinary carbon tools.

In England and on the Continent the new steels are widely used and have been much studied. The bibliography to be found on the ensuing pages comprises the most important papers specifically devoted to the constitution and structure of the class of steel under consideration. The subject has been abundantly and very ably studied with prints accompanying most of the articles. When we add to the papers listed the far more numerous and exhaustive contributions on composition, treatment and operating tests it is obvious that only some research of amazing magnitude, or attack by radically new methods or insight, would be worth the trouble.

As most of the illustrations of the structures of high-speed steels are in the French and English journals and either on common printing paper or of inferior magnification, the accompanying reproductions are offered that the established forms may be more clearly seen. Some of the grain structures and transition stages are possibly novel, if so their further interpretation is necessarily delegated to those of more experience and discernment than the author.

Bibliography.

1. "Microstructure of Steel Quenched from the Melting-Point", by Albert Sauveur.
The Metallographist, 3 (1900); p. 244.

One print of a chrome-tungsten steel at 250 diameters shows austenite and cementite and relative hardness.

2. "Les Aciers au Chrome", by L. Guillet.
Revue de Metallurgie, I (1904); p. 155.

Excellent presentation of the chrome-steels.

3. "Aciers au Tungstene", by L. Guillet.
Revue de Metallurgie, I (1904); p. 263.

Gives diagram of structures found and forecast, with summary of the carbides of tungsten and tungstides of iron.

4. "Les Aciers Rapides a Outils", by H. le Chatelier.
Revue de Metallurgie, I (1904); p. 334.

Subject very fully discussed; diagram of a bar heated and quenched at one end, only, shows soft metal, the zone of martensite, the cellular zone and the coarse exterior produced by the maximum heat. Four good prints accompany the paper. Transitions are indicated as gradual and uniform, no special zones.

5. "Contribution a la Theorie des Aciers Rapides", by F. Osmond.
Revue de Metallurgie, I (1904); p. 348.

Wholly academic discussion with no work or prints.

6. "The Development and Use of High-Speed Tool Steel", by J. M. Gledhill.
Journal of the Iron and Steel Institute (British), LXVI (1904-II); p. 127.

Paper chiefly devoted to composition and cutting tests, but accompanied by five prints, decidedly mediocre.

7. "Comparison des Proprietes et Classification d e s Aciers Ternaires", by L. Guillet.
Revue de Metallurgie, II (1905); p. 350.

Describes the tungsten steels as pearlitic or double carbide, and gives diagram of limiting compositions.

8. "The Types of Structure and the Critical Ranges on Heating and Cooling of High-Speed Tool Steels under Varying Thermal Treatment", by H. C. H. Carpenter.
Journal of the Iron and Steel Institute (British), LXVII (1905-I); p. 433.

Twenty-seven prints accompany this important paper; the prints at 30 diameters are of small account while the few at 1,000 diameters are only about an inch square.

9. "Recherches Recentes Faites sur les Alliages Industriels -Leur Importance", by L. Guillet.
Revue de Metallurgie, III (1906); p. 155.

States that for commercial work the chrome-tungsten steels should be of fine martensitic structure with the carbides fully dissolved by long enough heating at high temperature. No illustrations.

10. "Quarternary Steels", by L. Guillet.
Journal of the Iron and Steel Institute (British), LXX (1906-II); p. 1.

A most massive article. Twelve prints reduced from 200 diameters accompany. Strongly affirms that maximum hardness corresponds with total disappearance of the carbides. States that too rapid cooling gives inferior hardness due to formation of gamma-iron. ".... a well quenched high-speed tool steel should not reveal the pronounced presence of any constituent." Annealing only increases carbides without further alteration of structure.

11. "Tempering and Cutting Tests of High-Speed Steel", by H. C. H. Carpenter.
Journal of the Iron and Steel Institute (British), LXXI (1906-III); p. 377.

Another extensive paper accompanied by twenty-five prints. Small specimens are quenched from a series of temperatures. The author notes the increasing size of the polyhedra as the temperature of quenching is raised. Magnifications are low while oxidation and scratches appear to have confused the issues.

12. "Aciers Chrome-Tungsten", by L. Guillet.
Revue de Metallurgie, IV (1907); p. 5.

Describes extensive investigations; quenches from different temperatures; finds time required to dissolve carbides at various temperatures and that the hardness is greatest when such are in solution. 16 photomicrographs accompany.

13. "Function of Chromium and Tungsten in High-Speed Steel", by C. A. Edwards.
Journal of the Iron and Steel Institute (British), LXXVII (1908-II); p. 104.

A masterly discussion of the subject accompanied by much experimental data: analyses, heating and cooling curves, hardness tests and photomicrographs.

14. "The Constitution of Carbon-Tungsten Steels", by Thomas Swinden.
Journal of the Iron and Steel Institute (British), LXXX (1909-II); p. 223.

Refers mainly to the heating and cooling phenomena.

15. "The Chemical and Mechanical Relations of Iron, Chromium and Carbon", by J. O. Arnold and A. A. Read.
Journal of the Iron and Steel Institute (British), LXXXIII (1911-I); p. 249.

Describes and illustrates limited areas which contain troostite, sorbite, granular and laminated pearlite.

16. "Microskopische Untersuchung einiger hochlegierten Sonderstähle", by Felix Fettweis.
Stahl und Eisen, 32,2 (1912); p. 1866.

A valuable article dealing chiefly with the cast condition of the high-speed steels, showing how later structures (after working and heat treating) depend on this first condition. Thirty-six prints, 1 3/4 ins. dia., at 40, 45, 50, 75, 80, 100, 350, 600 and 1,000 dias. magnification are given on three pages. Through this source the author learned of etching with sulphurous acid.

17. "Die Fortschritte deutsche Stahlwerke bei der Herstellung hochlegierte Schnellarbeitsstähle", by G. Schlesinger.

Stahl und Eisen, 33, 1 (1913); p. 929. Rejoiner by Poldihütte, same, 33, 2 (1913); p. 1196.

Mainly concerns cutting ability, but five good prints are shown and the constitution as influenced by quenching strongly brought out.

18. "Aciers a Outils", by M. Denis.
Revue de Metallurgie, XI (1914); p. 4.

A massive paper on the cutting efficiency of steels, but relating specifically to the constitution of high-speed steel when it is found that varying carbon from .3 to 1.3% does not change the hot-hardness. The Herbert testing machine is used. High-speed tools are tempered between 400 and 600°C. for hot cutting, with 690° as the limiting temperature above which hot-hardness acquired by quenching begins to be lost.

19. "Etude sur les Proprietes Generales des Aciers a Outils", by M. Denis.
Revue de Metallurgie, XI (1914); p. 569.

A monumental paper full of precision and new conceptions; shiefly concerning cutting tests but reflecting strongly on constitution of the high-speed steels when it is shown that variation of 100° from best quenching temperature affects hardness slightly, and that physical tests on cold samples are not correlated with greatest efficiency under hot working conditions.

20. "The Chemical and Mechanical Relations of Iron, Tungsten, and Carbon, and of Iron, Nickel, and Carbon", by J. O. Arnold and A. A. Read.
Paper read before the Institution of Mechanical Engineers (British), March 20, 1914. Reported in the Iron and Coal Trades Review, March 27, 1914.

A very suggestive paper, emphasizing the probability of dissolved iron tungstide and the progressive hardening on quenching from 850° to 1,150°C.

The Materials Investigated.

The samples of steel available for the work were small bars of commercial high-speed tool steel bought in the open market. Rekord and Poldi came in bars 3/8 by 1/2 inch; Rekord came uniformly some 3 inches long while Poldi was broken to about the same length. Blue Chip, Ark, Novo and Bethlehem came in 1/4 inch square lengths which were broken to about 5 inches.

With the exception of Rekord, all the bars came in the annealed condition, rather hard it is true, yet drillings could be obtained with carbon steel tools in quantity sufficient for the chemical analyses. Rekord was annealed by slow cooling after long heating in a cylinder packed with lime.

The analyses as obtained by Lesser and Perlstein in their investigation are given on page 8. It will be seen that all the steels are of the same general class and rather closely related in composition. Tungsten occurs from 12.99 to 17.88%; chromium varies from 1.50 to 3.90%; carbon from .46 to .70%. Manganese is highest at .43% in Bethlehem and ranges down to none in Poldi. Phosphorus and sulphur are low in all cases; silicon is high at .48% in Novo and quite low in all the others. Neither molybdenum nor vanadium could be detected in any sample.

The heat treatment which Lesser and Perlstein imposed on the samples consisted in placing the bars in an electric carbon-resistor furnace and allowing the temperature to rise to a pre-determined point at which it was held during ten minutes; after withdrawing one bar of each sort at the end of these ten minutes and quenching the bar instantly in a strong air blast, the furnace temperature was raised to the next desired point and another set of bars, one of each variety, was removed and quenched. In this way, by doing the work on two or three days, bars were finally quenched from 920°, 980°, 1,040°, 1,100°, 1,160°, 1,210° and 1,280°C. This gives, including the annealed sample, eight bars of each of the six steels, forty-eight in all.

Admitting the possibility of mistakes in identification or temperature of quenching and allowing that in the matters of previous treatment, period of heating and suddenness of quenching there should have been more precision, yet, the samples serve well in supplying an excellent range and many transitions of structure in high-speed steel.

Chemical Composition.

(From Thesis by Lesser and Perlstein,
Armour Institute of Technology, 1914.)

	Rekord	Blue Chip	Ark	Bethlehem Novo		Poldi
Tungsten	13.69	13.63	12.99	16.82	17.88	17.56
Chromium	2.35	2.48	3.90	1.50	2.54	2.33
Carbon	.56	.70	.46	.60	.52	.58
Manganese	.06	.28	.07	.29	.43	.00
Phosphorus	.01	.05	.02	.03	.04	.03
Sulphur	.003	.008	.025	.015	.011	.009
Silicon	.18	.18	.13	.48	.28	.17
Nickel	nil	nil	nil	nil	nil	nil
Molybdenum	nil	nil	nil	nil	nil	nil
Vanadium	nil	nil	nil	nil	nil	nil

Outline of the Work.

Although the specimens had been ground, polished, etched and inspected by the previous investigators, it was necessary to resurface in all cases.

The surface already smoothed was ground on the emery stone until thoroughly plane. Grinding with emery dust on canvas then removed the coarse scratches, after which polishing with tripoli on canvas eliminated the fine scratches. A final slight polish with rouge on felt left the surface to be dried with alcohol and the piece ready for etching.

Each specimen was examined in the polished condition before etching; this seldom revealed more than slight evidence of the carbide droplets or benches due to some great change in the structure. Etching consisted in holding in a 2% solution of picric acid in alcohol for 10 minutes, washing in water then momentarily dipping in a 10% aqueous solution of nitric acid; after washing thoroughly in water, swirling a few times in alcohol and quickly wiping with absorbent cotton the specimen was placed in a dessicator until used.

If the steel was not sufficiently attacked by this treatment it was dipped in sulphurous acid solution one or more times until the structure became plain. To the naked eye sufficient attack is indicated by a dull, matte surface. In many cases the quickest and most perfect wiping after the alcohol hardly prevented stains which give a spotted or banded appearance under the microscope.

Provided the etching developed enough character in the surface, the piece was usually lightly repolished on chamois by hand using a fine silicious silver polish in a thin mud. This treatment is strongly recommended.

The equipment now available for taking the photomicrographs consists of a Leitz metallurgical microscope, purchased in 1911. The object is inverted over the objective and the bellows extension is horizontal.

A magnification of 500 diameters meets the demand for sufficient enlargement as well as showing a field large enough to be representative. The 6a objective, projection eyepiece II and bellows extended to 61 cm. gives this magnification. A piece of the ground green glass supplied with the instrument was used in all cases to give dispersed monochromatic light; each field required estimation of its brightness so that the diaphragm might be set to afford the right light for a strong plate in an exposure of from 30 to 40 seconds.

Both Imperial and Ortho-Nonhalation plates were used, the latter with the more success. Prints were made on Azo F, Hard X paper; hydroquinone developer for the plates and metol-quinone for the paper.

The hardness was obtained in the usual way with a recent model of the Shore scleroscope.

Details and Precautions.

In outline, the work is simple and straightforward; in detail, difficult and tedious.

The power-driven vertical polishing machine is the same as described by Sauveur; the two double wheels thus accomodate the emery stone, emery dust, tripoli and rouge keeping each on its own side. Speeded somewhat above customary, the preparing of a specimen with this outfit required some 20 minutes.

The novice has trouble to grind a surface flat, on the stone alone; experience soon overcomes this but much more skill is required to get the scratches out of a so planed surface without developing benches if more than one main structure is present. The reproductions show that scratches are hardly at all in evidence, in one or two cases the print was made practically at the edge of the metal, in which cases the fault may be excused. As to the success of polishing so as to get a smooth level field covering two main structures, the prints themselves bear witness.

In all the polishing work the principle used was to keep the specimen in continual motion, as refered to the wheel. This prevents parallel and deep marks developing at any time; the author considers it far better than holding fixed in one position, then polishing at right angles.

The etching itself is quite simple; one reagent or the other attacks enough if even moderate time is allowed. The development of the character of the surface must, of course, be followed under the microscope and stopped at the right point. Sometimes the proper amount was exceeded in an effort to discover every feature possible; in a case of this sort the specimen had to be entirely reground.

It was early noted that the extremely finely corroded surfaces of these steels oxidize badly on simple drying from the wet condition. After thorough use of alcohol and the quickest possible wiping with absorbent cotton, this source of false appearances became almost negligable.

For making photomicrographs of this magnification at Armour Institute it is absolutely necessary to protect the instrument from shock of vibration. The steel frame designed by the author met this difficulty. It is fully described and illustrated in The Chemical Engineer, XIX, 5; p. 186 (May, 1914).

The technique of making the exposure to get sharp, and strong, and uniform negatives is a matter of experience and judgement. On a given specimen it is not difficult to determine the length of exposure; but the surfaces ranged all the way from matte and almost black to smooth, bright and almost mirror-like.

Obtaining the exact focue for the plate under 500 diameters requires some experience.

The matter of the uniform illumination is by far the most difficult part of the technique. It cannot be found by visual inspection, but must be gained by practice with the plates. The trick is to get the cone of light uniform across, neither stronger nor weaker in its center, nor more intense on one side.

Spherical aberration is not always overcome and may even be augmented by rounding of the surface of the steel.

Needless to say, many of the negatives required shading to make fair prints. At the best many prints are poor, this in spite of discarding over 50% of the plates made.

In the published reproductions, as found in the journals, all these defects are often glaringly apparent; we believe to have attained a fair measure of success in this respect.

With the excessively fine markings on the specimens, yet with the enormous contrast due to carbide spots or due to the cellular structures, it requires much skill to gain the proper range of tone in the finished print. As a rule the aim was to get as much contrast as possible; in some cases not enough has resulted, in others the prints are too hard and lacking in detail. Many appear just about right.

The copper half-tone plates were made through a 150-line screen.

The Structures Obtained.

It will be found that the prints following show all the sorts of grain structure which are known to exist. Most of the prints display only "componental" grain; the texture due to this sort of structure is susceptible of extreme fineness as is abundantly shown. Several of the specimens have beautiful cellular structure, alone to be seen. Others have the cellular structure, besides this two or more components present giving dual grain. Lastly, a few of the prints show componental and cellular grain with one or more constituents arranged to constitute an entirely distinct "structural" grain. These varieties of grain structure have been previously described and illustrated in the case of the carbon steels by the author in The Chemical Engineer; May, 1914.

Intermediate stages showing partial development of the structures are found and shown; these are one of the most valuable features of the investigation here recorded.

The actual structural substances of steels of this sort have received the names of "double carbides", "pearlite", "sorbite", "troostite", "martensite" and "austenite". The carbides are generally in the most conspicuous forefront, present in nearly every print. The pearlitic field prevails in the annealed specimens nor is difficult to recognize by appearance, etching or hardness test. For lack of definite and conclusive evidence as to the presence of such structures the terms "sorbitic" and "troostitic" are omitted from the present consideration. On the other hand, martensite and austenite are the main constituents of the hardened samples. There is apparently a wide range between the two structures; it is here that new designations might well be introduced instead of between martensite and pearlite as is generally needed when considering the carbon steels.

The inhibiting effect of the high tungsten on the decomposition of the solid solution is everywhere in evidence. It is well to keep in mind that these steels can be cooled from the higher temperatures without appreciable deflections in the cooling curve. Every single specimen responds readily to the magnet.

The annealed specimens are seen in Figs. 1, 2, 3, 4, 5 and 6. The carbide droplets are conspicuous; the grounds are mainly pearlitic, granular, with occasional spots which seem less differentiated from the solid solution. These etch strongly with picric and nitric acids, also with sulphurous acid. Scleroscope hardnesses are, in order, 24, 40, 20, 27 and 19.

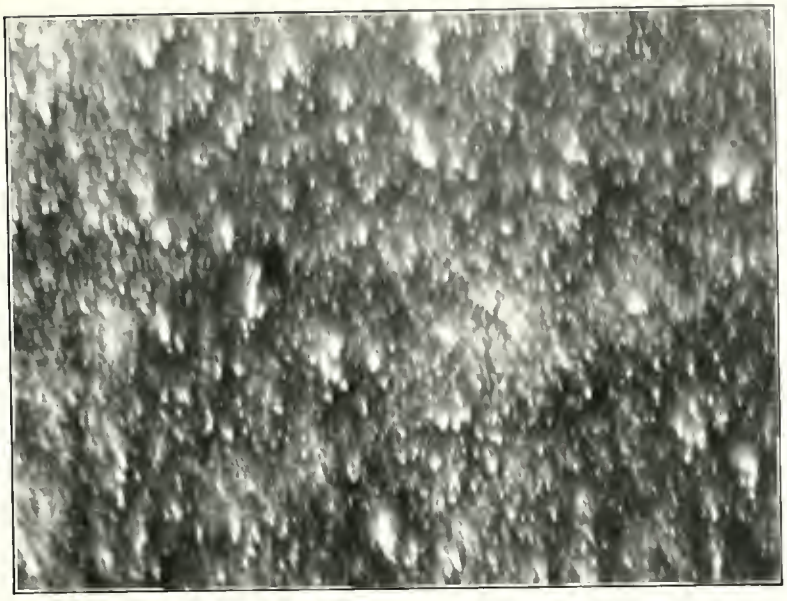

Fig. 1. Rekord, annealed, 500 dia.

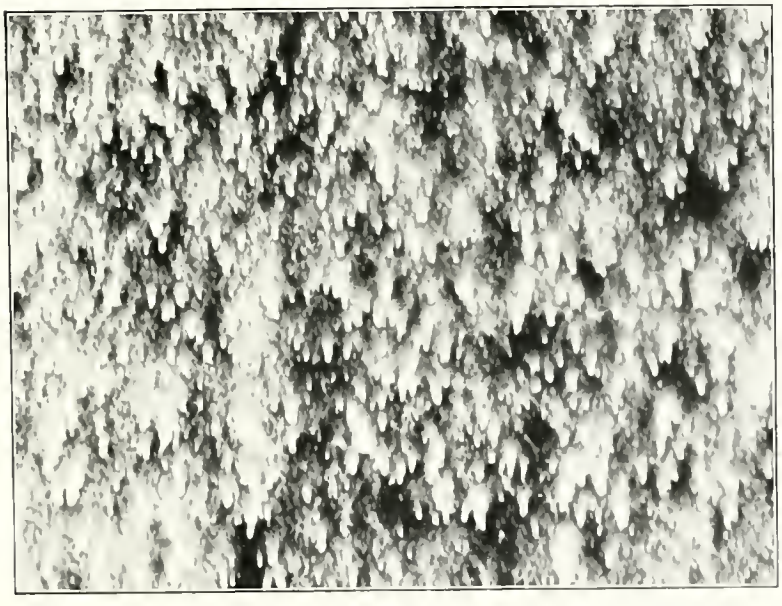

Fig. 2. Blue Chip, annealed, 500 dia.

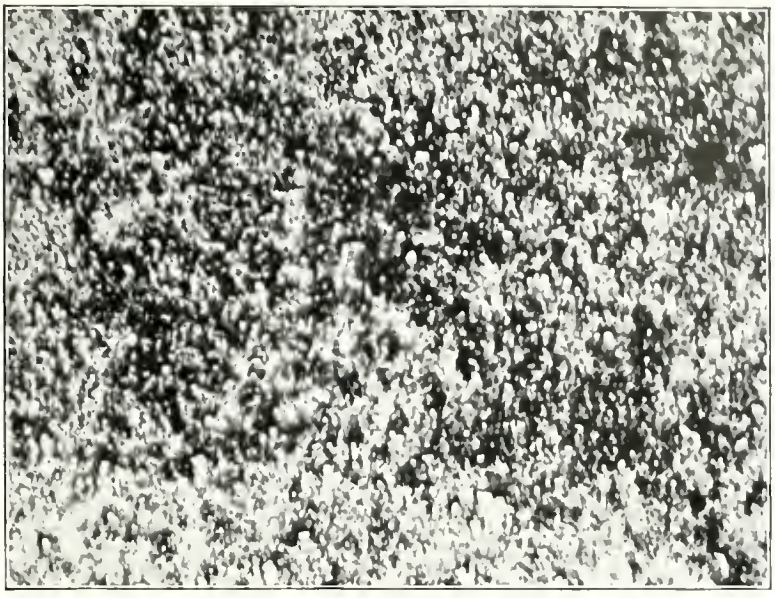

Fig. 3. Ark, annealed, 500 dia.

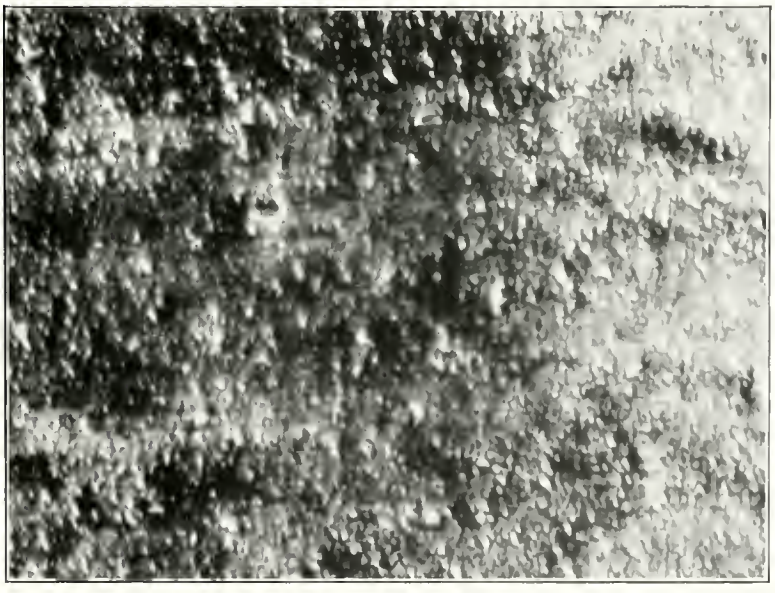

Fig. 4. Novo, annealed, 500 dia.

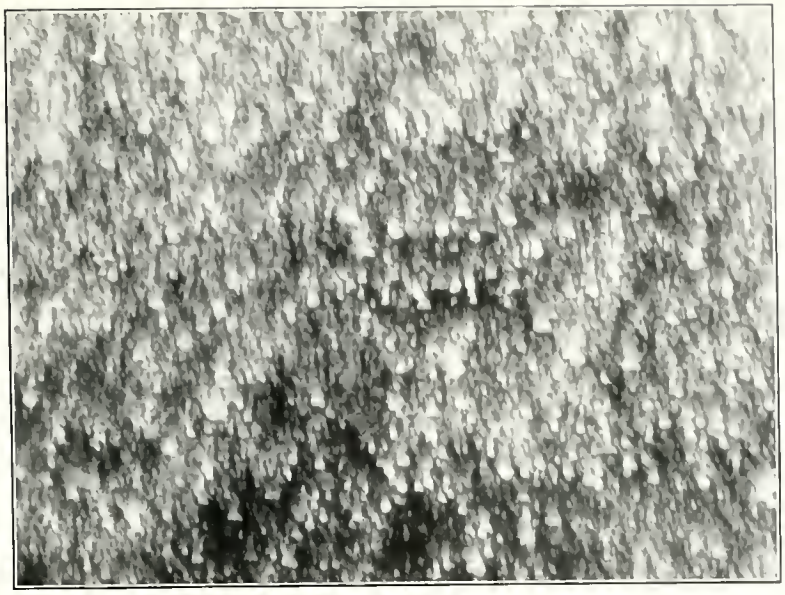

Fig. 5. Bethlehem, annealed, 500 dia.

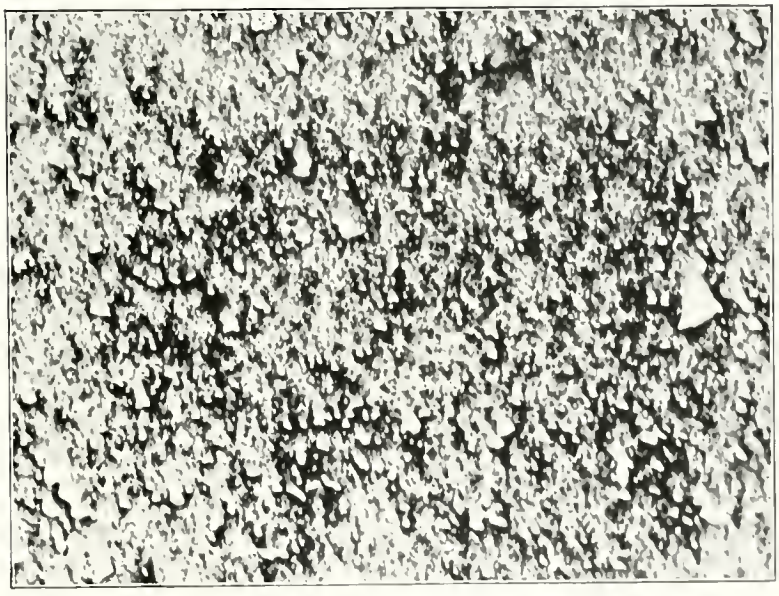

Fig. 6. Poldi, annealed, 500 dia.

Structures on Quenching from 920°.

Figures 7, 8, 9, 10, 11 and 12 on pages 18, 19, and 20 indicate typical structures as obtained by quenching in the air blast from the above temperature.

Rekord, hardness around 45, shows a granular field, resembling pearlite, but with the white granules predominating. This is exactly the reverse of the appearance with the more advanced pearlite, which shows fewer white points and more of the dark field. Plenty of carbide droplets are visible in Fig. 7.

Blue Chip, quenched at this temperature, also shows a granular background and abundant carbide droplets. In testing the hardness of the prepared surface it was found that scleroscope readings ranged from around 50 on one edge to around 82 along the opposite side. No structural differences were noticed which would account for the varying hardness.

Ark shows a general distribution into pearlitic areas between martensitic spots as seen in Fig. 9. Hardness is about 70; no carbide droplets are seen.

Novo, with hardness around 60, displays carbide droplets in a pearlitic ground.

Bethlehem, hardness around 76 and up to 80, has a beautifully cellular core surrounded by a pearlitic fringe, outside of which is an envelope of enormous grain size. Fig. 11 shows the cells of the core; they are finely striated, clearly defined, have a few carbide droplets in odd places and many dark spots which appear to be pits in what we designate as the austenite. The huge exterior cells are shown in Fig. 49 on page 46; the pearlitic zone on page 50.

Poldi, hardness around 45, shows in Fig. 12 a quite uniform pearlitic ground and a few carbide droplets. This is one of the most characteristic pearlitic fields which are found.

In general, it is evident that heating to 920° and quenching has increased the hardness of the steels but that the heating has not been long enough or high enough to dissolve the carbides or pearlite. Specimens Ark and Bethlehem are exceptions to the general statement, which, in the possibility of lack of precision in identity and manipulation must be passed over.

Fig. 7. Rekord, quenched at 920°; 500 dia.

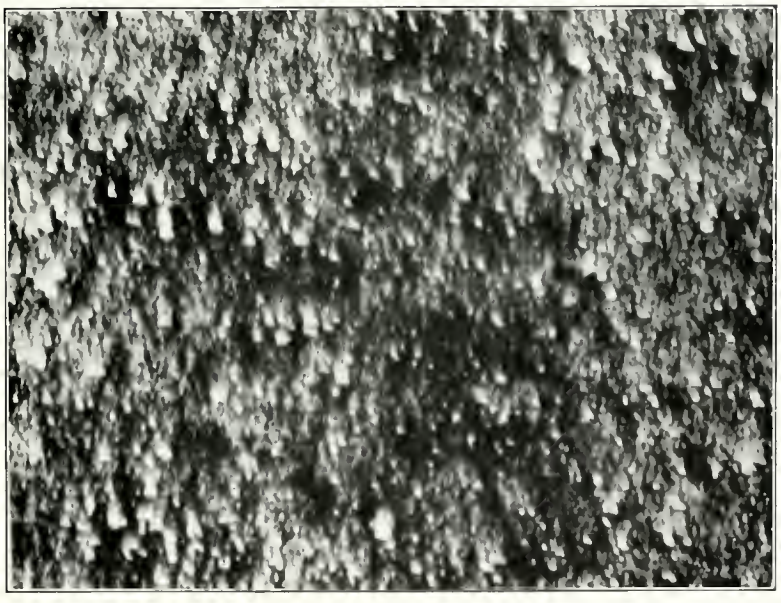

Fig. 8. Blue Chip, quenched at 920°; 500 dia.

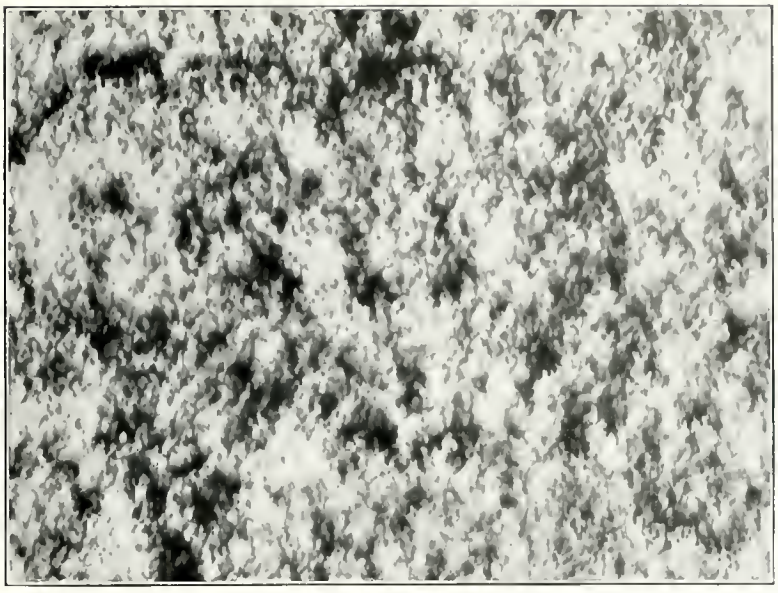

Fig. 9. Ark, quenched at 920°; 500 dia.

Fig. 10. Novo, quenched at 920°; 500 dia.

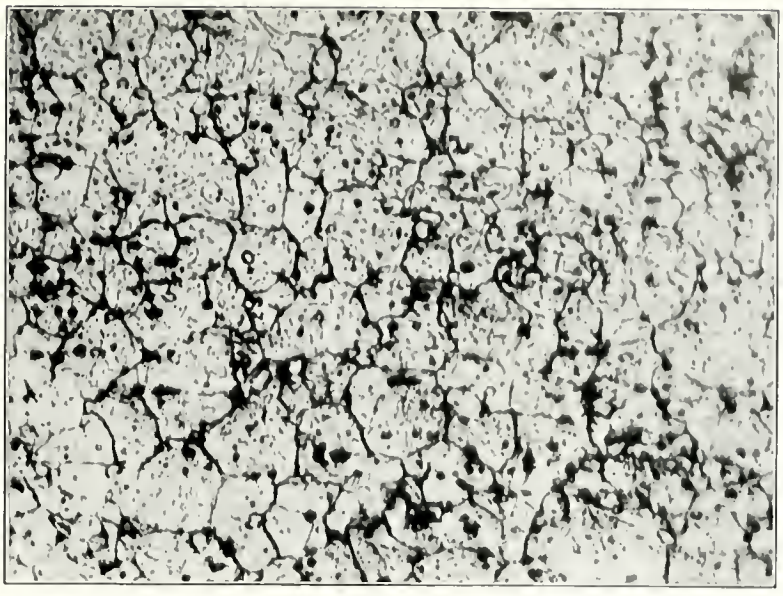

Fig. 11. Bethlehem, quenched at 920°; 500 dia.

Fig. 12. Poldi, quenched at 920°; 500 dia.

Structures on Quenching from 980°.

Figures 13, 14, 15, 16, 17 and 18 on pages 22, 23 and 24 show the respective appearances as obtained on the samples quenched from 980°.

Rekord, with a mean hardness of 56, shows pearlitic areas between spots of harder and more white material. Fig. 13 is a field of the latter, martensitic structure prevailing. The carbide droplets are numerous though small.

Blue Chip has a mean hardness of 77; it runs up to 86 at one point. This is the highest number found for any of the samples. Fig. 14 shows the many carbide droplets. The steel etches scarcely at all with picric and nitric acids, but sulphurous acid brings out the fine lines of the almost massive martensite.

Ark is similar to Blue Chip without the carbides. The piece runs up to 78 in hardness, is not tarnished by picric and nitric acids although sulphurous easily brings out the fine markings of Fig. 15.

Novo is not as hard as the previous, 60 being the mean number. The reagents tarnish easily, showing that the transformation to solid solution is not complete. No carbides are visible.

Bethlehem and Poldi have fallen off in hardness to 52 and 30, respectively; acids attack, although less easily with Bethlehem than Poldi. The latter has the large and characteristic granules of pearlite. Carbides are abundant in both.

Quenching from this temperature is thus able to give a massive martensite of the non-cellular variety, hard and not easily attacked by acids.

Fig. 13. Rekord, quenched at 980°; 500 dia.

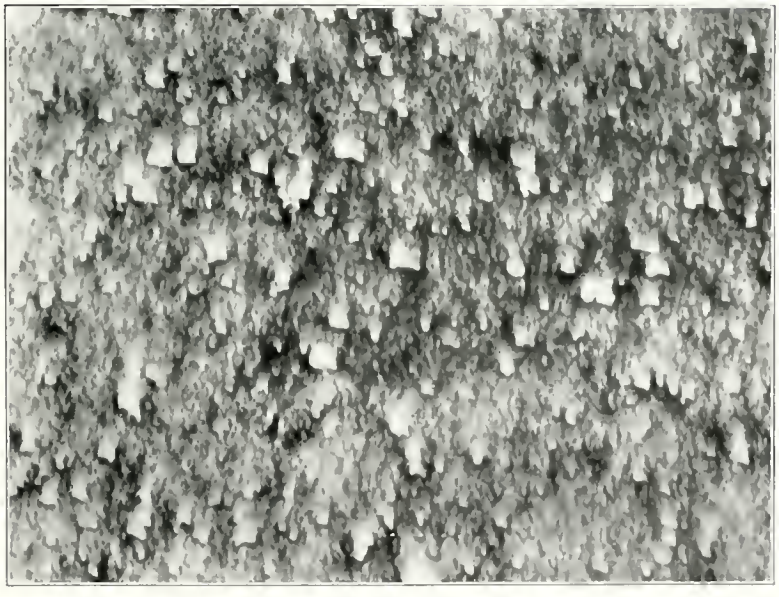

Fig. 14. Blue Chip, quenched at 980°; 500 dia.

Fig. 15. Ark, quenched at 980°; 500 dia.

Fig. 16. Novo, quenched at 980°; 500 dia.

Fig. 17. Bethlehem, quenched at 980°; 500 dia.

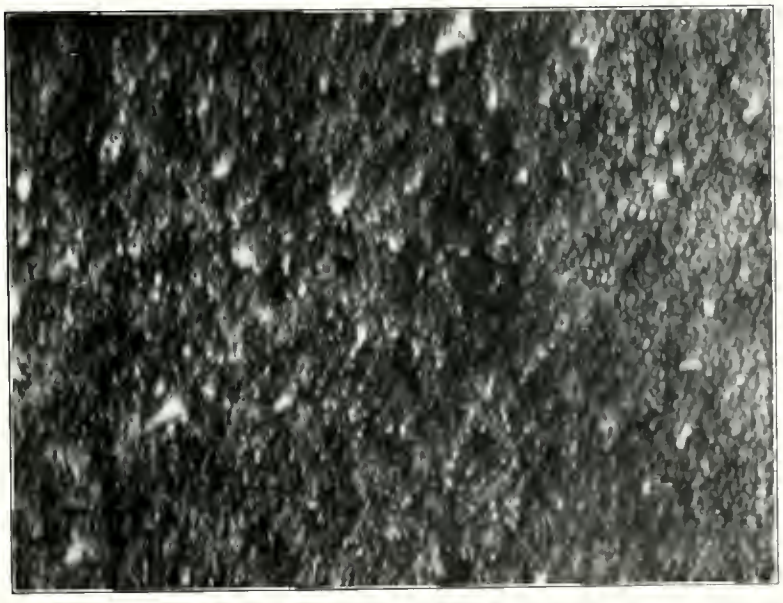

Fig. 18. Poldi, quenched at 980°; 500 dia.

Structures on Quenching from 1040°.

Figures 19, 20, 21, 22, 23 and 24 on pages 26, 27 and 28 represent the structures obtained on the respective samples quenched at 1040°.

According to the scleroscope Rekord has not been completely hardened at this temperature; its number is only 41. However, it does not etch as easily as the annealed steel and in the print (Fig. 19) appears partly pearlite between larger areas of the structure resembling martensite.

Blue Chip has quite a uniform, crinkly to granular, slowly etching martensitic nature. Some carbide droplets are present. With a mean hardness of 72, increasing to 84 in places, we have a typical structure of a high-speed steel as quenched at about this temperature.

Ark, likewise, gives a regular martensitic structure and has good hardness -67 to 74. Fig. 21 shows the etching carried so far as to bring out the inherently fine granular nature which with less corrosion appears more like Fig. 20.

Novo is similar to the above in all respects.

Bethlehem shows the effect of the temperature in the next step beyond the regular granular martensite. The crinkly lines which normally break across the entire field now are confined around numerous local areas which remain comparatively smooth. It is plainly the stage between two structures better defined, granular martensite on one hand and cellular austenite on the other. The hardness which might be expected at this temperature is not reached for the scale reads around 55, highest at 61.

Poldi brings the next stage, which shows a full cellular nature with the granulations of the martensite largely submerged. Hardness of this sample is around 57, highest at 62. A consideration of the regular martensitic structure and then Bethlehem and Poldi at this quenching temperature as seen in Figs. 23 and 24 leads to the interpretation that the nodules of martensite determine by their size the grain size of the subsquent cellular austenite. In other words, the grains of austenite do not start to grow from infinitely numerous nuclei but from predetermined units and are in their origin of a minimum size, of which the units of Figs. 23 and 24 in this series are possibly a minimum. Certainly none of the steels studied in this investigation displayed a cellular structure of appreciably finer grain or closer texture than Fig. 24. Several other samples have equally fine grain and from this as the lower limit, many illustrations will indicate the growth and development of the grain size with longer and higher heating.

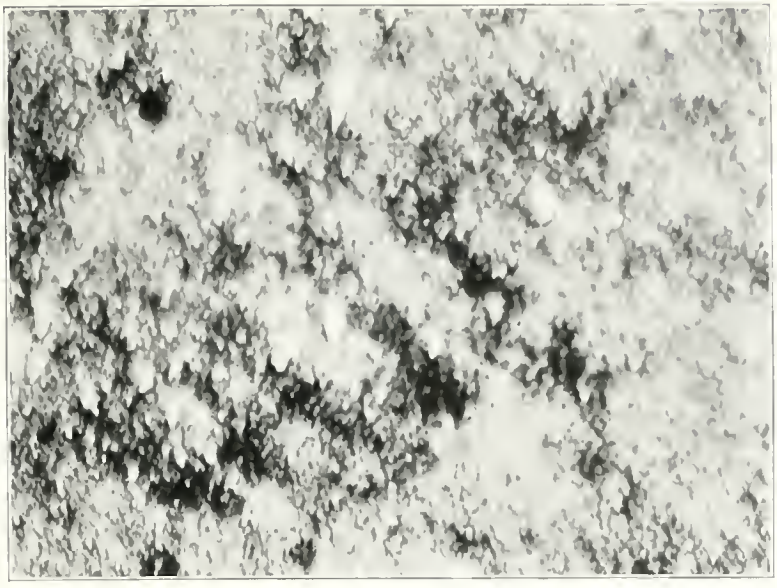

Fig. 19. Rekord, quenched at 1040°; 500 dia.

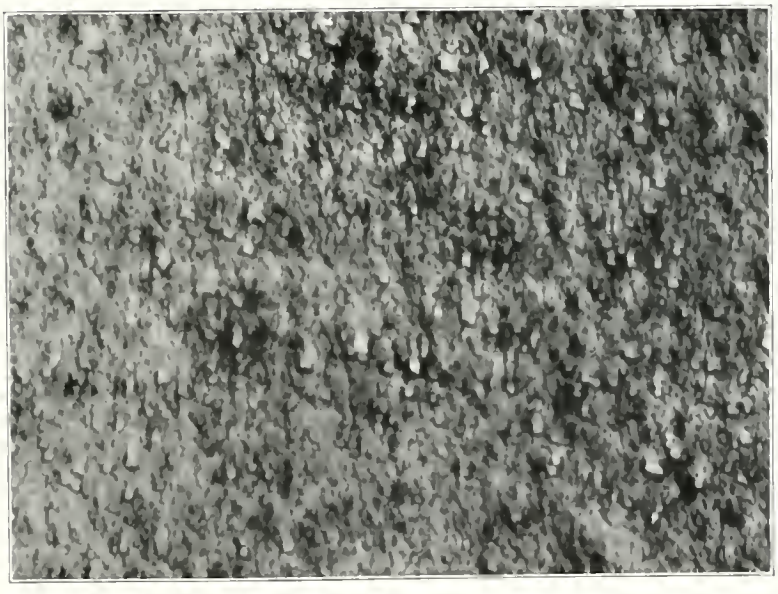

Fig. 20. Blue Chip, quenched at 1040°; 500 dia.

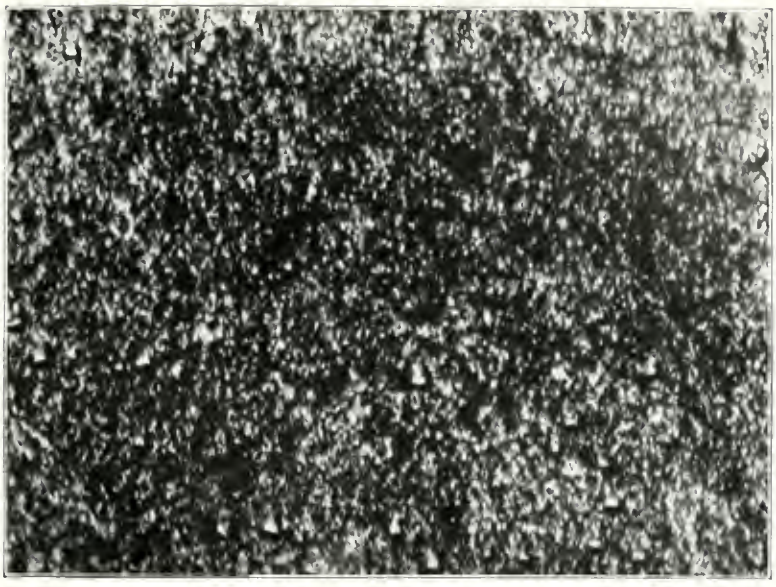

Fig. 21. Ark, quenched at 1040°; 500 dia.

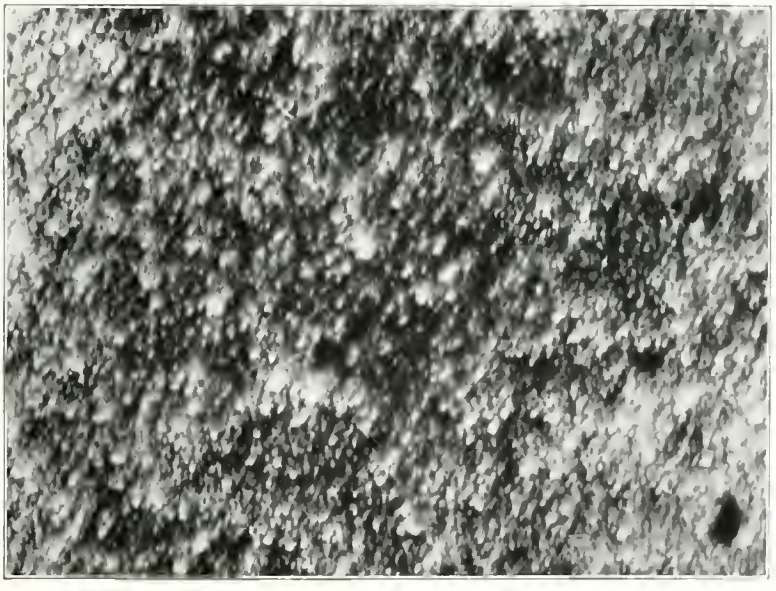

Fig. 22. Novo, quenched at 1040°; 500 dia.

Fig. 23. Bethlehem, quenched at 1040°; 500 dia.

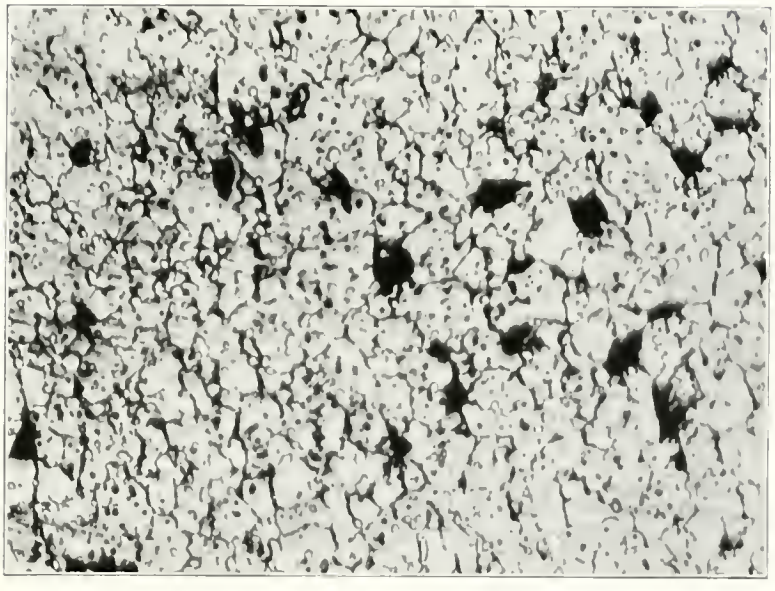

Fig. 24. Poldi, quenched at 1040°; 500 dia.

Structures on Quenching from 1100°.

Figures 25, 26, 27, 28, 29 and 30 on pages 30, 31 and 32 are of the specimens quenched at 1100°.

Etching Test.

Steel.	Picric, then Nitric Acid.	Sulphurous Acid.
Rekord	Strong Attack	Heavy Attack
Blue Chip	Slight Attack	Easily Tarnished
Ark	Slight Attack	Strong Attack
Novo	Slight Attack	Easily Corroded
Bethlehem	Slight Attack	Easily Corroded
Poldi	Medium Attack	Easily Corroded

Hardness by Scleroscope.

	Low.	Mean.	High.
Rekord	39	41	45
Blue Chip	74	80	84
Ark	52	62	76
Novo	55	65	72
Bethlehem	40	60	65
Poldi	44	47	52

No marked development of a cellular nature appears in any of the steels quenched at 1100°. As the heating and quenching of the steels was done on some three different days it is quite possible that these samples were not soaked as long as some quenched at lower temperatures; this would fully account for the slight general relapse to nothing but martensitic or lower forms.

It brings out the important condition of length of heating at temperatures even lower than the one from which quenching takes place.

Rekord and Poldi have a tendency to show pearlitic areas, while the print of Bethlehem (Fig. 29) is mainly pearlite on the left side. This is fairly well exempl - ary of the transition between pearlite and martensite; an equal amount of etching leaves one darkly granular, the other smoother, lighter, yet striated and slightly granular.

Blue Chip, Ark and Novo have normal character for this quenching temperature after a medium soaking.

All have plenty of carbide droplets.

Fig. 25. Rekord, quenched at 1100°; 500 dia.

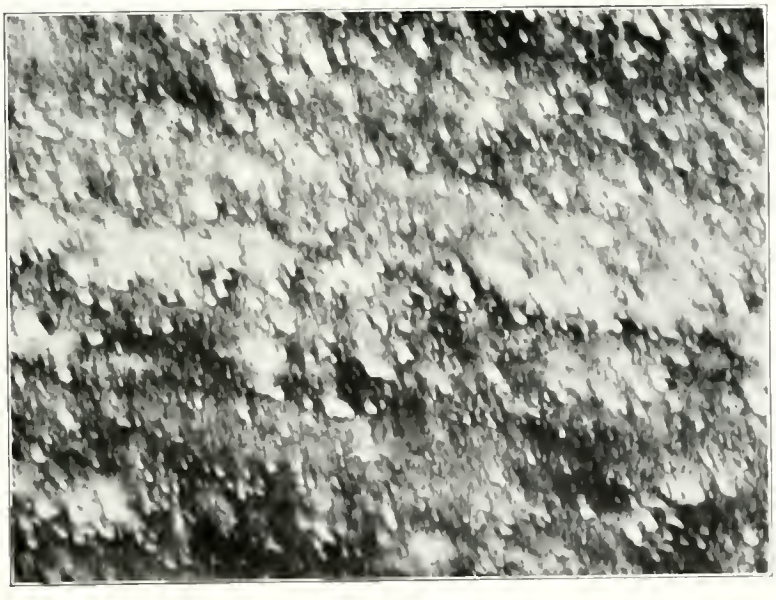

Fig. 26. Blue Chip, quenched at 1100°; 500 dia.

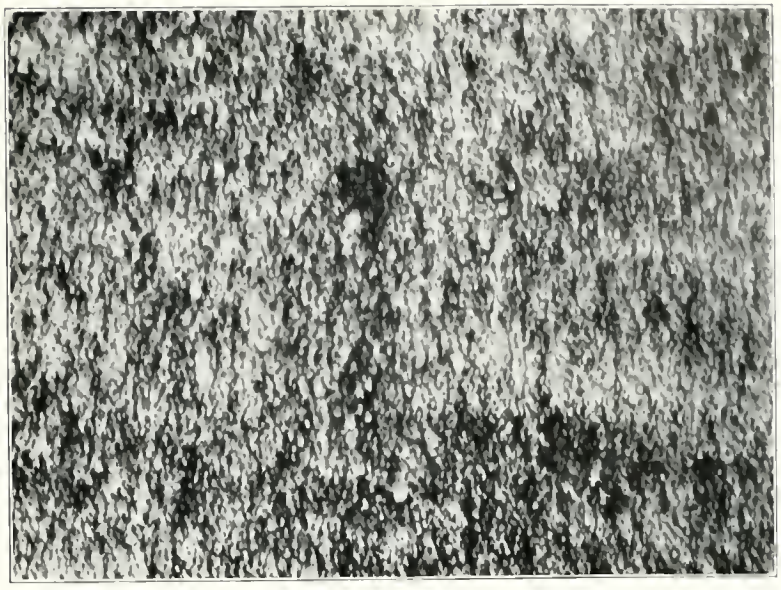

Fig. 27. Ark, quenched at 1100°; 500 dia.

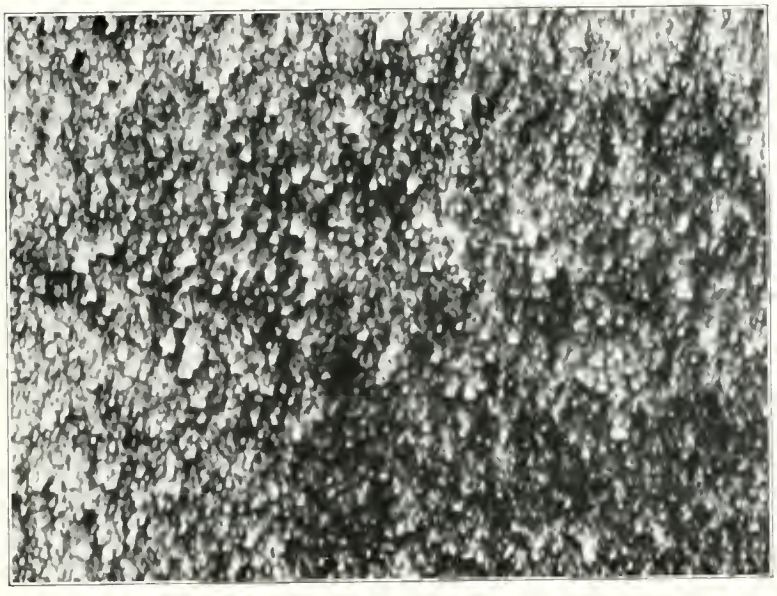

Fig. 28. Novo, quenched at 1100°; 500 dia.

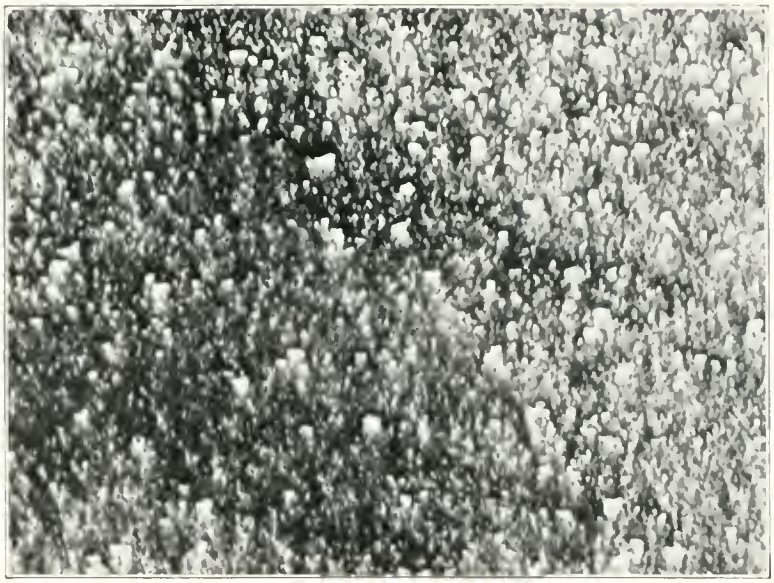

Fig. 29. Bethlehem, quenched at 1100°; 500 dia.

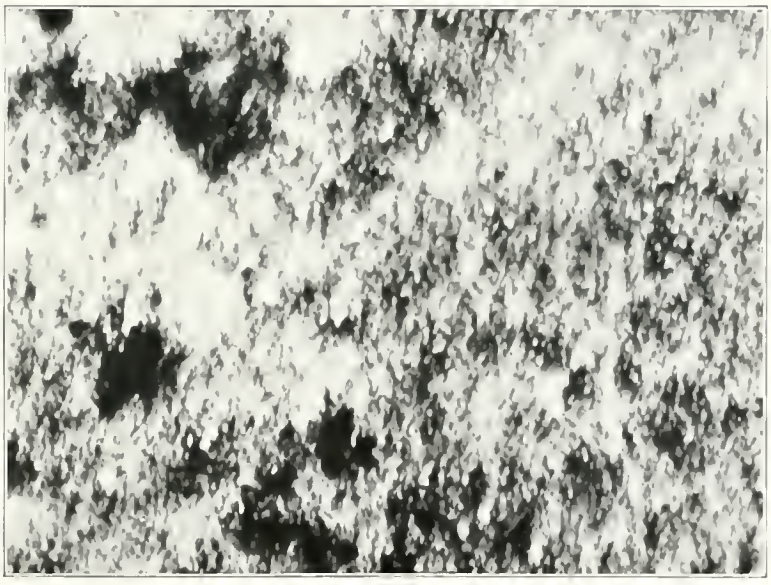

Fig. 30. Poldi, quenched at 1100°; 500 dia.

Figures 31, 32, 33, 34, 35 and 36 on pages 34, 35 and 36 are selected views from the structures at this heat.

From this range of temperature up, the microscope reveals an astonishing and bewildering world of appearances.

After reaching the temperature at which the change to cellular austenite from granular martensite takes place, the grains of the austenite grow quickly in size. From our work the range of the change is evidently from 1050° to 1150° and probably dependent on the soaking period.

The change progresses through the specimen as the time and temperature of heating increases. The transition also may be marked by a peculiar pearlitic zone between, this perfectly plain to the naked eye after etching as a dark line, or zone, on the face of the specimen which separates the inner core from the outer periphery.

Our choice of views may now extend over many interesting appearances, but is unfortunately limited to a few typical prints.

Rekord, with uniform hardness of about 52, yields from a crinkly lined field to granulations only with sulphurous acid. Fig. 31 shows the latter, plainly uniform martensite.

Blue Chip, mainly quite soft and from 30 to 40 by the scale, goes up to 60 on one side. Even sulphurous acid does not tarnish; however, under the microscope it is seen that the field is yet bright and polished but subdivided into huge grains and sub-grains. Fig. 32 is an excellent representation. Other sections through the specimen would likely supply wholly different results.

Ark is likewise untarnishable even by sulphurous acid. Picric and nitric acids cannot even dull but under the microscope it is found that they have faintly outlined the handsome cellular structure which sulphurous acid develops and is shown in Fig. 33. The hardness is only 20 to 40; the bright surface is only slightly pitted with v-shaped dots.

Novo has a mixed structure grading from and between martensite to austenite; hardness is 34 to 60. Fig. 34 is of an intermediate spot. Cell boundaries are developing about the smoother areas. Acids tarnish only in spots.

Bethlehem has a tarnishable core through the section exposed by grinding. This core colors brownish but is eaten into scarcely at all. Hardness varies from 40 to 60. Fig. 35 is one spot in the core; surface still striated but deeper lines making about the unifying nodules.

Poldi has hardness from 45 to 50; is untarnishable by any acid; from Fig. 36 it is plainly in the distinct yet early stage of finely cellular austenite.

From this exposition it is positively clear why steel makers insist that quenched high-speed tools have their exterior ground off before use.

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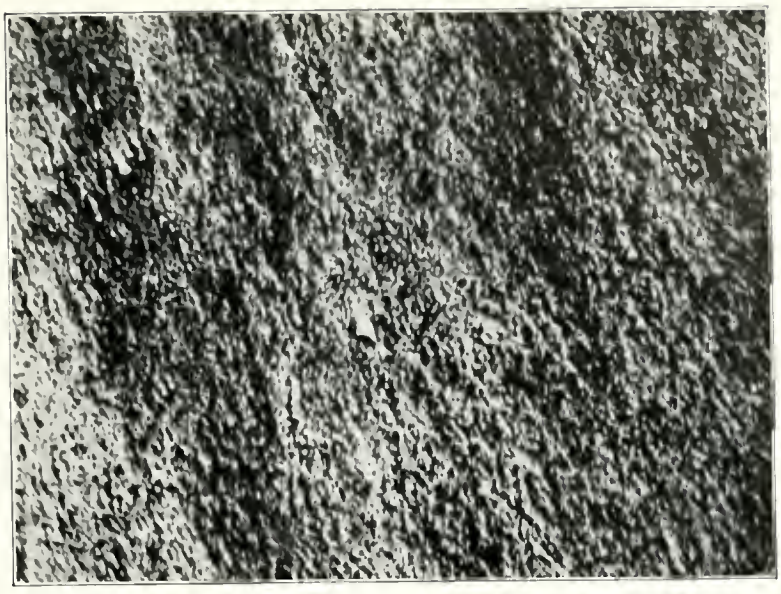

Fig. 31. Rekord, quenched at 1160°; 500 dia.

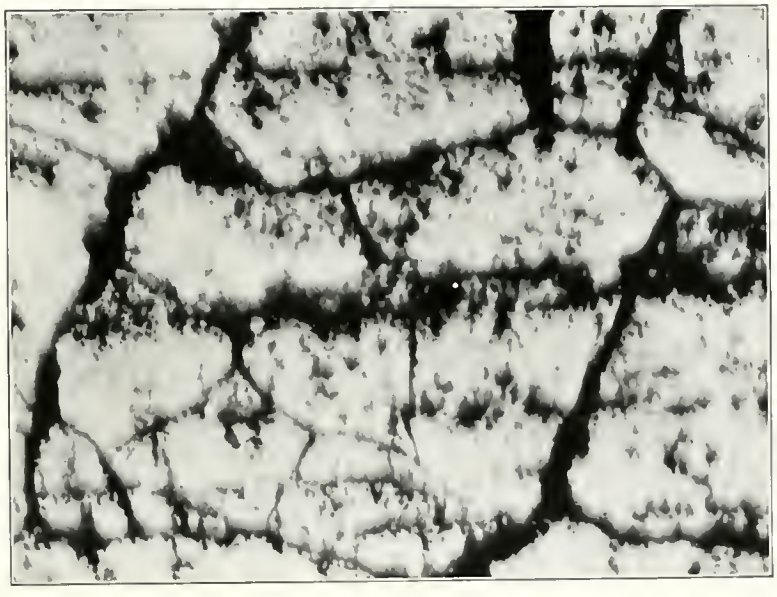

Fig. 32. Blue Chip, quenched at 1160°; 500 dia.

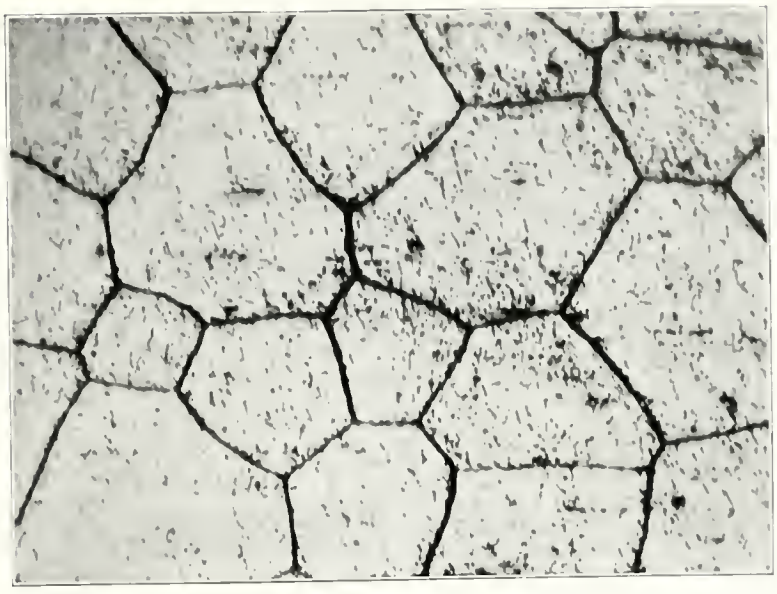

Fig. 33. Ark, quenched at 1160°; 500 dia.

Fig. 34. Novo, quenched at 1160°; 500 dia.

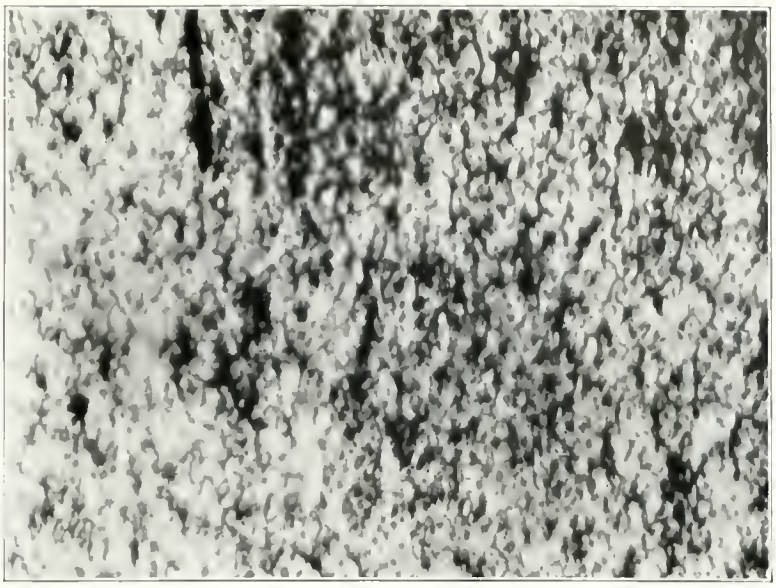

Fig. 35. Bethlehem, quenched at 1160°; 500 dia.

Fig. 36. Poldi, quenched at 1160°; 500 dia.

Structures on Quenching from 1210°.

Figures 37, 38, 39, 40, 41 and 42 on pages 38, 39 and 40 are from the samples quenched at 1210°.

Rekord has its customary hardness of from 38 to 47 with mean around 42. Picric and nitric acids affect little but sulphur dioxide brings out the granular appearance of Fig. 37.

Blue Chip gradually outlines the distinctly cellular austenite as seen in Fig. 38. Its hardness is around 55, much less than the martensite gives. Carbides are present as silvery white and rounded spots on the surface slightly browned by sulphur dioxide.

Ark in the advanced martensitic stage in Fig. 39. Its hardness is low on one side at 45, toward the other it increases through 65 to mount up to 78 in spots on the opposite side along the long edge of the specimen.

Novo shows the beginning of cellular units although the hardness is rather that of martensite, up to 74 as maximum. From Fig. 40 one might imagine that the grain had advanced enough to be called austenitic, as confirmed by the etching test. Yet, after all, the martensitic lobes are not much rounded out as they should be after full coalescence, while the hardness is also high.

Bethlehem likewise appears on the boundary between the two better defined solid solutions. Acids etch slowly, hardness is up to 75 and strong lines begin to appear running through the still positively granular martensite.

Poldi is between martensite and austenite. In some spots it is granular, in others markedly cellular. Hardness is from 54 up to 61. Fig. 42 shows a stage in the building of the higher structure.

Carbide droplets are present in all of the specimens.

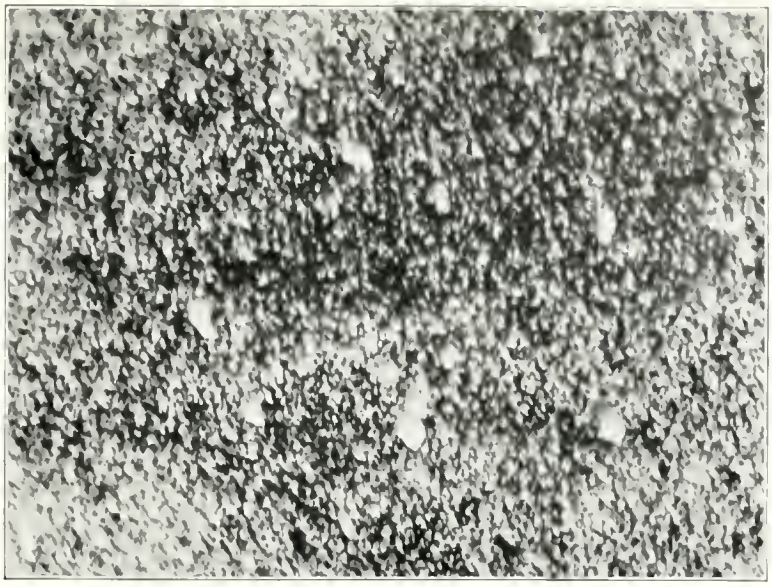

Fig. 37. Rekord, quenched at 1210°; 500 dia.

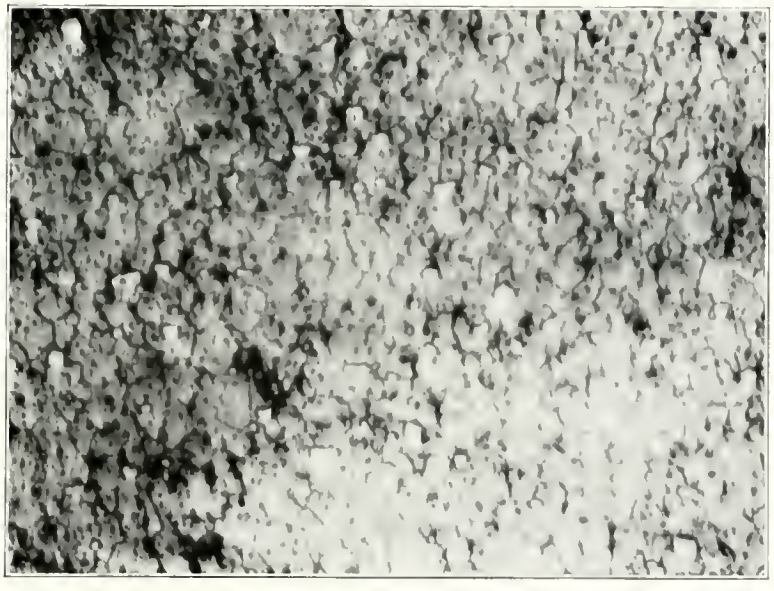

Fig. 38 Blue Chip, quenched at 1210°; 500 dia.

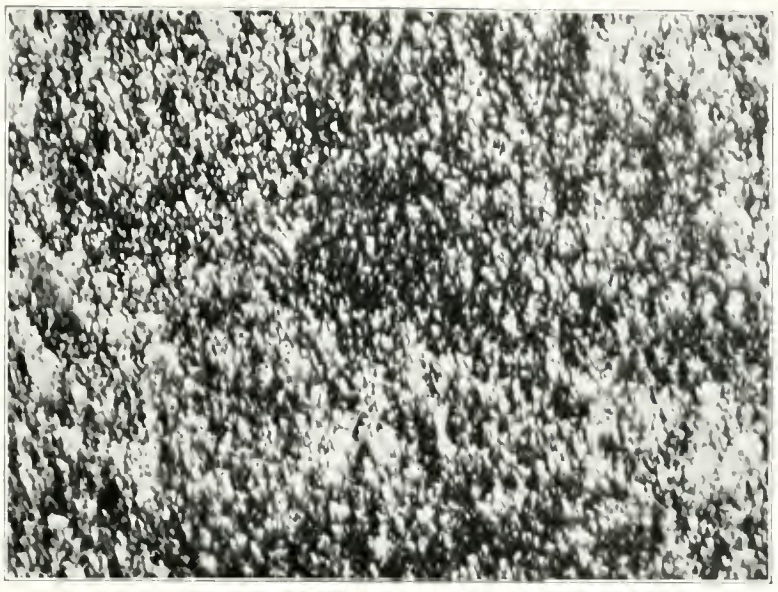

Fig. 39. Ark, quenched at 1210°; 500 dia.

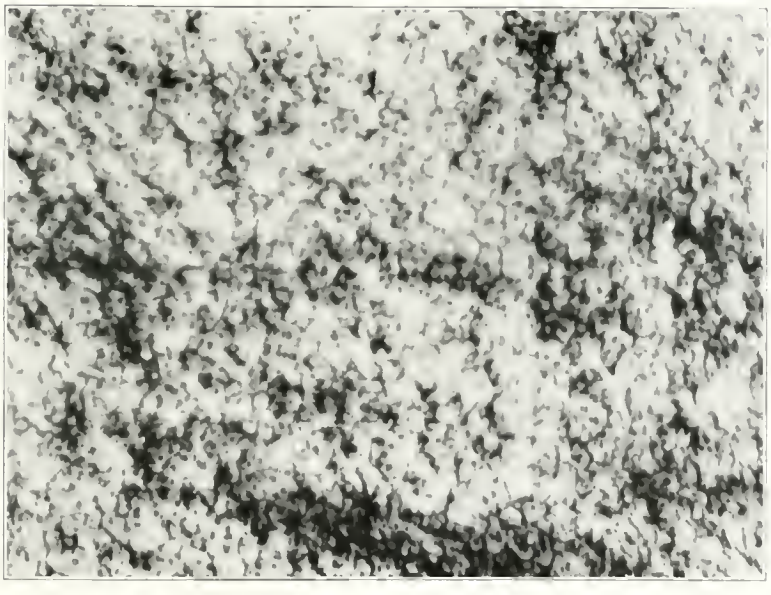

Fig. 40. Novo, quenched at 1210°; 500 dia.

Fig. 41. Bethlehem, quenched at 1210°; 500 dia.

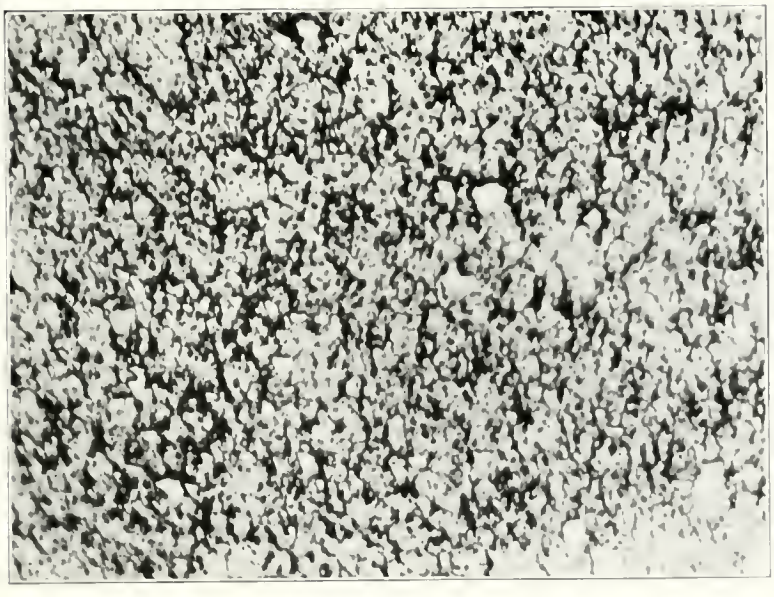

Fig. 42. Poldi, quenched at 1210°; 500 dia.

Structures on Quenching from 1280°.

Views of results obtained from quenching at 1280° are given in Figs. 43, 44, 45, 46, 47 and 48 on pages 42, 43 and 44.

Rekord is apparently in the early instead of later martensitic condition. This is the only steel which does not approach an austenitic type with the higher temperatures. In physical size the pieces were just the same as Poldi and in composition practically the same as Ark, both of which comport themselves properly at the higher temperatures. Hardness of the piece is from 39 to 47; etching and appearance shows the piece to be on the pearlitic side of martensite.

Blue Chip is likewise soft and easily etched and looks more like a steel quenched at 920° than one which has been heated to 1280°. The responsibility is likely on the numbering or heating. No trace of cellular outline is visible in either of the above.

Ark is a spotted specimen; the core is hard martensite and the exterior large grained austenite. Hard spots go up to 64 and the periphery goes down to 40. Fig. 45 is of a spot in the core which shows the lines of a large grained austenite already darting through the mass. Even in the center some localities show absolutely no trace of such markings, other spots have even better delineation than in Fig. 45. This is extremely interesting as being an entirely different way of generating austenite from the one discussed on page 25.

At this temperature Novo is quite like others already discussed. It is concordant with the temperature; soft austenitic parts of rather large cellular grain are of some 40 on the scale while other parts run up to 74. Fig. 46 is of a harder portion of the sub-austenitic nature. Etching is slow and mostly confined to bringing out the carbide droplets and the cell boundaries.

Bethlehem through the section exposed by the grinding, which is admittedly near the outside, is uniformly of large grain as seen in Fig. 47. Hardness is from 32 to 42 and etching is confined to pittings in the smooth face and enlarging the grain divisions. To the naked eye the acid-treated surface is still bright and reflecting.

Poldi, like Blue Chip, is quite out of accord with what should be found for the conditions. It was most likely quenched from 920°.

Fig. 43. Rekord, quenched at 1280°; 500 dia.

Fig. 44. Blue Chip, quenched at 1280°; 500 dia.

Fig. 45. Ark, quenched at 1280°; 500 dia.

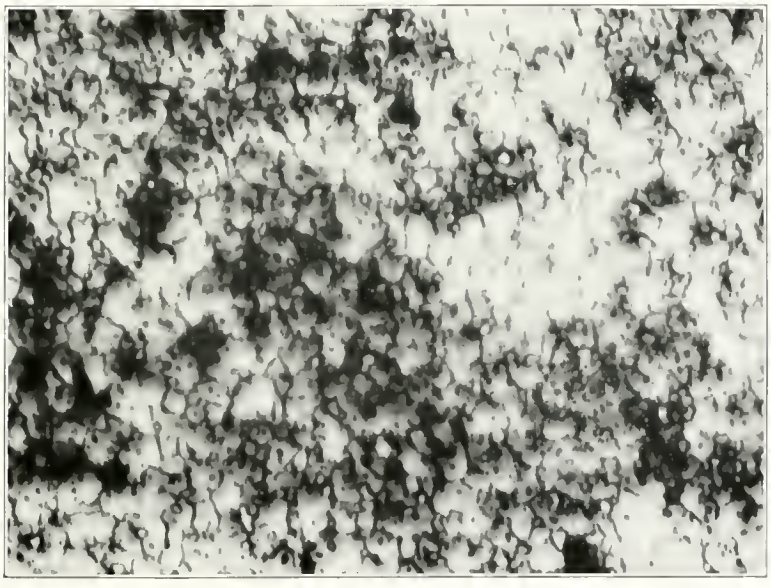

Fig. 46. Novo, quenched at 1280°; 500 dia.

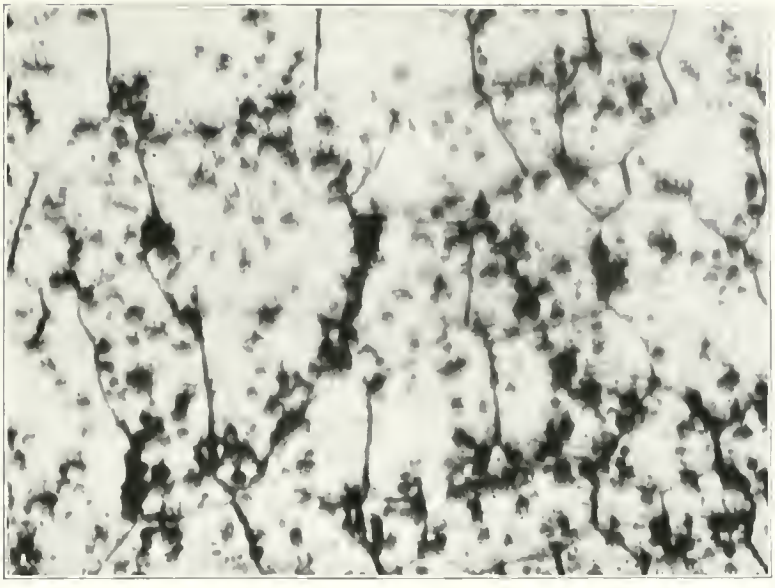

Fig. 47. Bethlehem, quenched at 1280°; 500 dia.

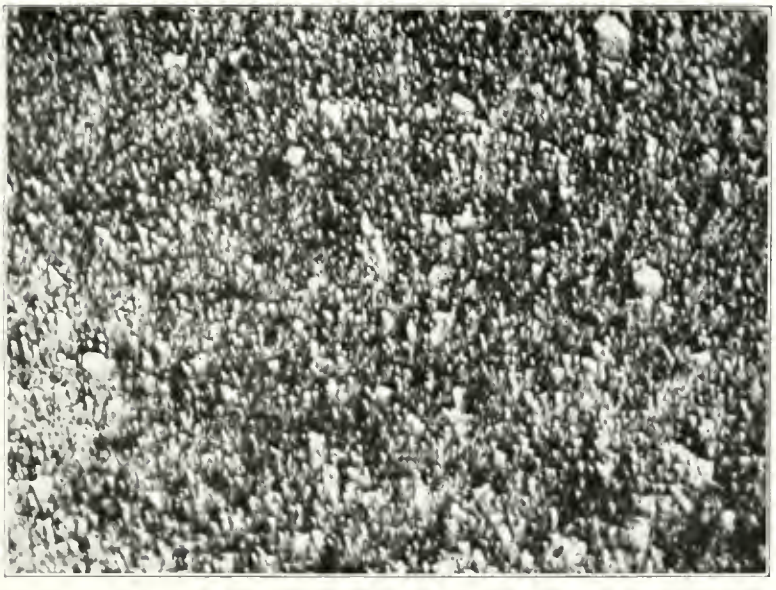

Fig. 48. Poldi, quenched at 1280°; 500 dia.

About Certain of the Large Grains.

Some of the more interesting large grain structures are shown in Figures 49, 50, 51, 52, 53 and 54 on pages 46, 47 and 48.

Fig. 49 is from the obviously misplaced specimen of Bethlehem, the core nature of which has already been seen in Fig. 11. This latter view is of the exterior shell. The austenite is slightly pitted and contains a few carbide droplets, otherwise nearly a polished surface. The grain demarkations are rather wide and in places even further widened by clumps of what appears to be pearlite. Etching with the stronger acid as is necessary to best show the finer cell structure of the interior corrodes this pearlite so deeply that it appears black in the print.

Fig. 50 is from an also possibly misplaced specimen of Poldi, alleged to have been quenched at 1040°. In this instance the grain is the largest seen in any of the specimens. These grains of such enormous size occur on the exterior, only, and may be so large that a print the size of Fig. 50 could be placed so as not to show a single boundary, the magnification being 500 diameters. In this case the lines are narrow but the surface is thickly pitted; the conclusion is that it is a case in which those constituents which make the broad lines have not migrated to the boundaries.

Fig. 51 from Novo quenched at 1160° and taken from the very edge of the piece (this accounts for the several scratches) where the material is soft gives quite a regular polyhedral grain. The thinness of the lines is unusual.

Fig. 52 is from Ark quenched at 1280°. The austenite interiors are conspicuously smooth and polished; the grain boundaries are equally burdened with bunches of pearlite. This is a peculiarity we do not remember having read about.

Fig. 53 is from Novo quenched at 1280°. It is the rather stereotyped representation of the large grained austenite.

Fig. 54 is from Bethlehem quenched at 1280°. Besides the bunching of pearlite along the grain boundaries there is a rib of carbide running through the pearlite. Here, again, is a structure which is possibly new. It is of course the same surface as Fig. 47, only more toward the outside. If this penetrated deeply it would make a most brittle and fragile material.

Ed

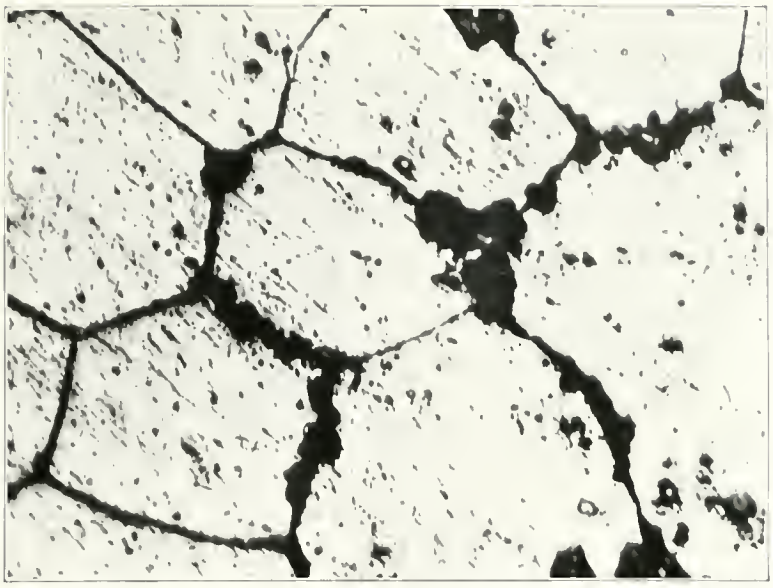

Fig. 49. From Bethlehem, quenched at 920°; 500 dia.

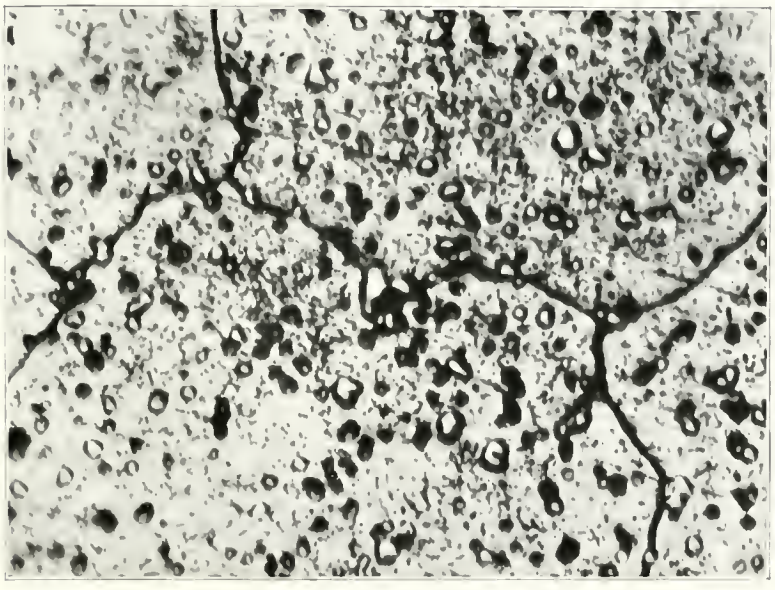

Fig. 50. From Poldi, quenched at 1040°; 500 dia.

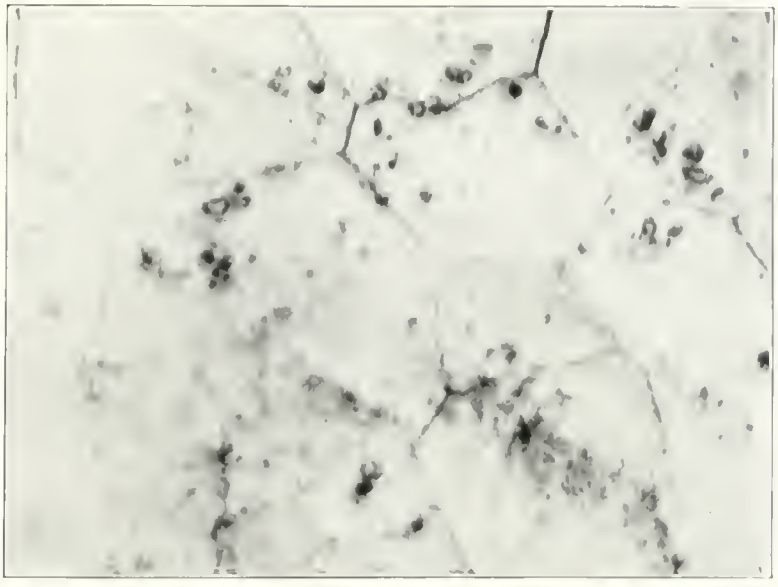

Fig. 51. From Novo, quenched at 1160°; 500 dia.

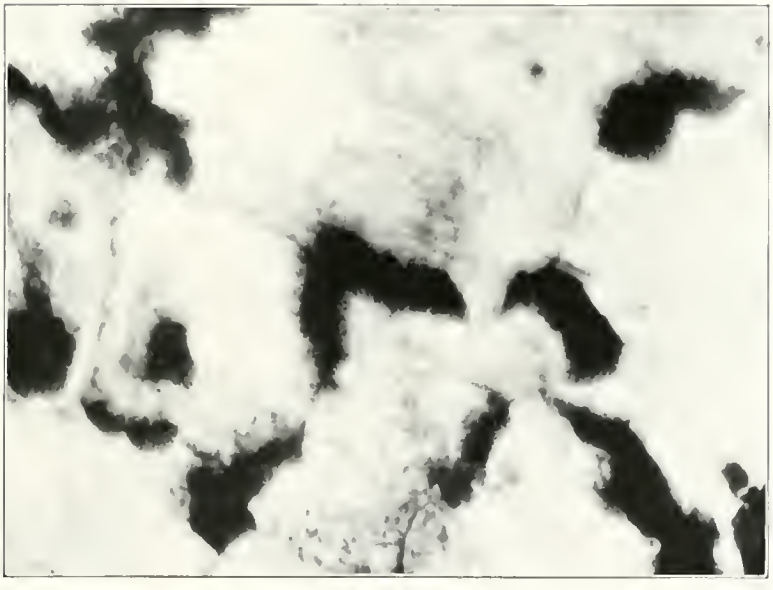

Fig. 52. From Ark, quenched at 1280°; 500 dia.

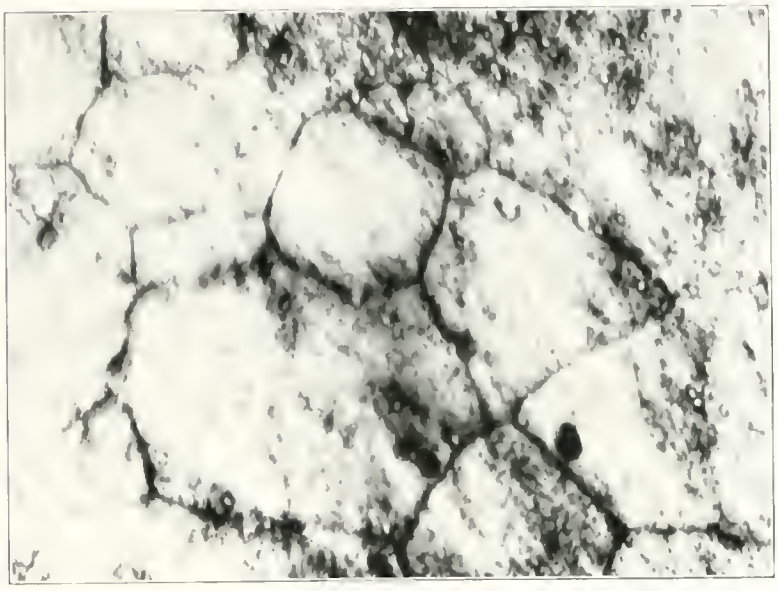

Fig. 53. From Novo, quenched at 1280°; 500 dia.

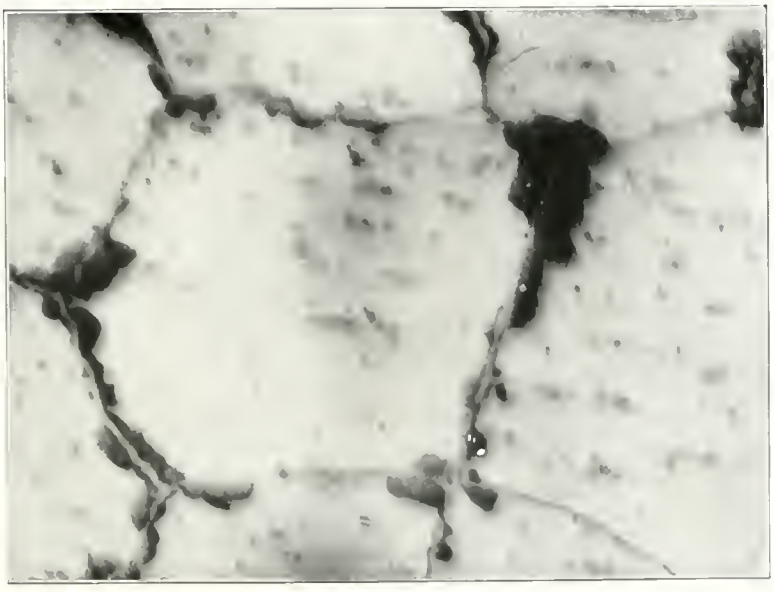

Fig. 54. From Bethlehem, quenched at 1280°; 500 dia.

Certain Transition Structures.

The transition stages in this sort of material offer peculiar opportunity for easy and detailed study. The limitations of the microscope are not hard to find, but a great deal is to be found for the seeking.

Fig. 55 is from Bethlehem, the same specimen probably erroneously marked as having been quenched from 920°. It was certainly heated far higher. The cut on page 50 shows massive martensite on one side and cellular austenite on the other, a zone of pearlite coming between. Fig. 55 was taken at a point where the zone is narrow enough to get both side materials on the plate. The austenite os of course on the outside of the specimen.

Fig. 56 is of the same zone in the same piece taken at a broad section of the zone. Two sorts of whitish areas are seen in the print; one sort is more striated than the other, constituting isolated units of the martensitic core. The second sort of white unit is smooth and polished, conspicuously identical with the grains of austenite from the outside of the piece. Both sorts are imbedded in the pearlite and some may even be far to the opposite side and wholly surrounded by the opposite material. This intermingling of the distinct units in a mass of pearlite is a remarkable phenomenon. It is anything but the gradual and progressive change most students of the subject commonly assume. On page 17 we have alluded to this specimen as having an austenitic core, and illustrated same. If we here refer to the core as martensitic it is because that at this particular point the mass does not have the cellular structure. Most of the core is cellular and hence austenitic; it is also hard and the grains are striated, indicating the later or last stage of what we call martensite. The same peculiarity has been mentioned in other cases.

Fig. 57 shows a boundary between two stages in the alteration of martensite, the normal and the sub-austenitic.

Fig. 58 is from the same steel but the sample quenched at the next higher temperature; here we have a transition from sub-austenite to normal austenite. It is one sort of transition between core martensite and exterior austenite.

Fig. 59 shows the same transition in Ark, quenched at 1280°. This is a wonderful transition: on the top side is normal brown etching martensite, below is large grained cellular austenite, silvery white. Between is the strangely arranged pearlitic zone and the meeting of the two solid solutions.

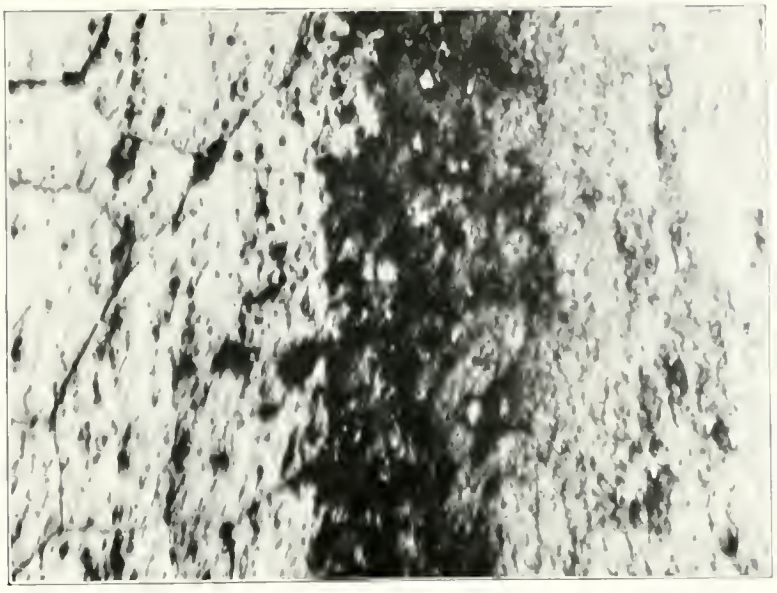

Fig. 55. From Bethlehem, quenched at 920°; 500 dia.

Fig. 56. From Bethlehem, quenched at 920°; 500 dia.

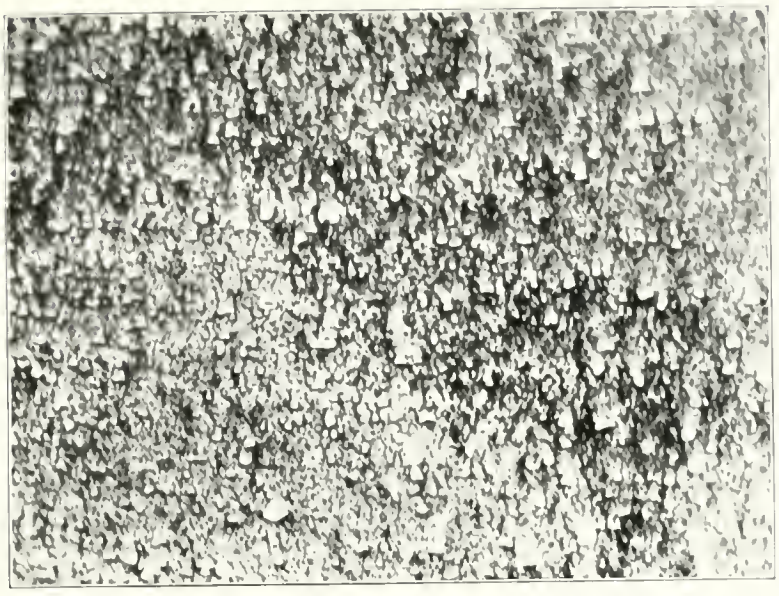

Fig. 57. From Bethlehem, quenched at 1100°; 500 dia.

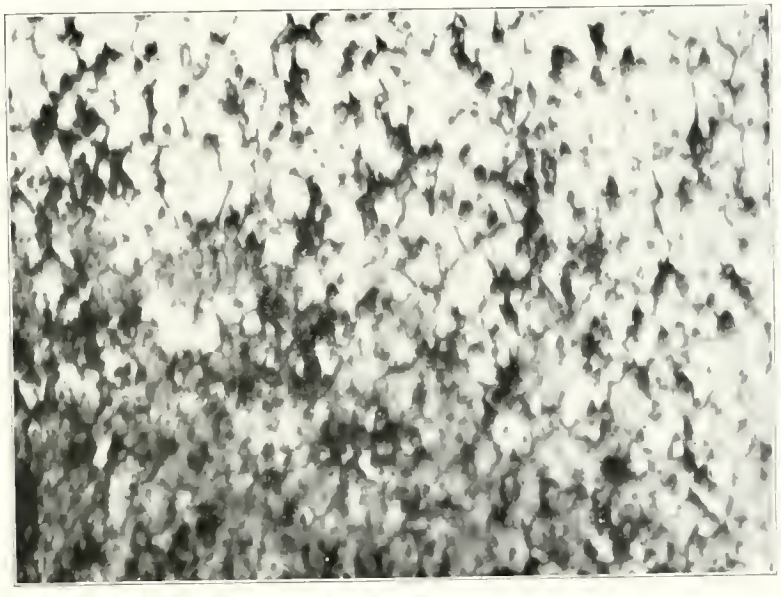

Fig. 58. From Bethlehem, quenched at 1160°; 500 dia.

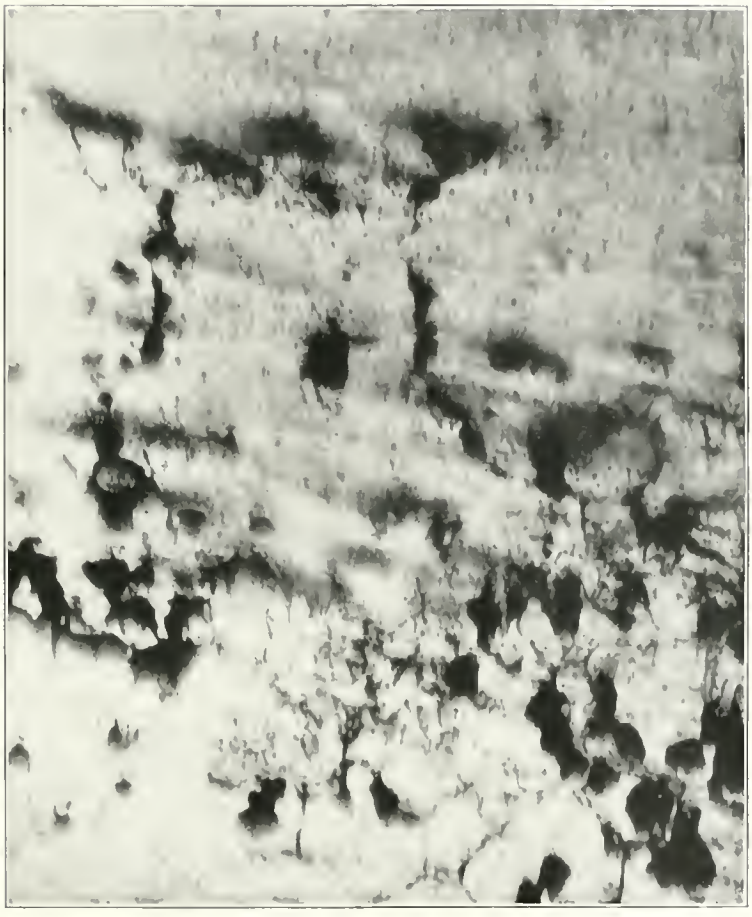

Fig. 59. From Ark, quenched at 1280°; 500 dia.

Summary.

In a general way the study demonstrates typical structures for pearlite, martensite and austenite in high-speed steels. Transitions from one to the other are described and illustrated; what happens with excessive heating of the material is also shown.

From pearlite to martensite looks like a short step accomplished largely within the molecules and sparingly portrayed in microscopic character. It is true that from softest pearlite to hardest martensite the step is easy to recognize; it is plain by scleroscope, etching and appearance; yet, the pearlite is also capable of considerable hardening while it still etches and looks quite the same. Unquestionably there is a new solid solution formed with the completed change.

From martensite to austenite the steps are drawn out and accomplished with deliberation; numerous degrees may be caught and studied. The loss of granularity by martensite and the taking of the cell form by the austenite has possibly been studied only in less detail previously.

The further grain growth of austenite and the advance of the pearlitic fringe is a novel and undescribed phenomenon. Is it the rate of heating which determines whether high carbon segregates shall be bunched along the grain boundaries, held in nodules throughout the grain, or bodily assimilated? Further investigation may answer the question, all three of the cases are plainly shown in prints.

The carbide rib through the pearlite areas of the mammoth austenite we have been taught to expect, but how shall we explain the chemistry and physics of the advance of the pearlite zone.

The best method of heat-treating high-speed steel has been demonstrated by tests too overwhelming to be in any degree contreverted; the fine-grained austenitic structure has likewise long been proclaimed as the aim of heat treatment. If anything, the experiments here recorded tell us how <u>not</u> to treat the steel and throw us back on the time-honored method of soaking thoroughly at a low heat, then bringing to incipient fusion at the end and quenching. Such a course assumes that the martensite-austenite transformation (page 25) takes place rather uniformly throughout the specimen while the short interval of high heat gives no chance for the appreciable advance of mammoth austenite behind its pearlitic fringe. A slight grinding of the

surface will then expose fine austenite as the cutting edge for hot work.

Cold hardness is seen to be highest developed in the median martensitic stage; this ensues all the way from below 1000° to above 1100° with moderately short soaking. Some loss of cold hardness with the advance of structure toward sub-austenite and fine austenite is apparently inherent in the same and does not matter for hot work according to the best authorities.

The results are wholly in accord with the best information on the subject. The function of carbon and exact composition as regards tungsten and chromium amount to little within the limits of the composition of the steels used.

The precision required in an investigation of this sort has not been met in a degree to make the work of the fullest significance as regards temperature-structure correlation; in general it is good but several glaring exceptions are found.

The samples should have been sliced through the medial line longitudinally instead of just grinding off one side.

In grinding, etching and photographing the cry is always for better and better technique which one wills but cannot obtain. Photographic definition is always striven for and in no way attained.